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(54) Abstract Title

Seismic data processing method

(57) A method of seismic prospecting which can be used to spatially locate and separate geological events, such as reflected and refracted waves or P (longitudinal) and S (shear) waves, and calculate their dip and direction of dip. Use is made of multi-axis seismic sensors arranged in a borehole. The data generated by each component of the multiple axial sensor is assigned further data designating its orientation in space. The data from each multi-axis sensor is then further processed in parallel so that, from among the waves received (polarised waves in particular) at each multiple axis sensor, those whose direction of polarisation is parallel with the direction of propagation may be selected. The detectors are generally three axial and the source can be located either on the surface, in the same or in another borehole. The advantages are that directions from which polarised waves come can be determined, the source position can be found and seismic events can be located in space.

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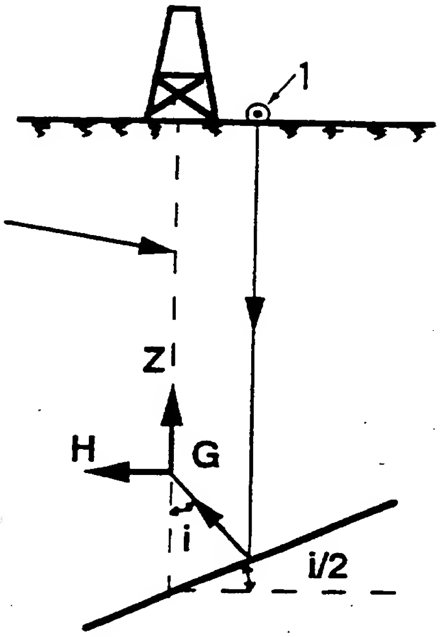


Fig. 1

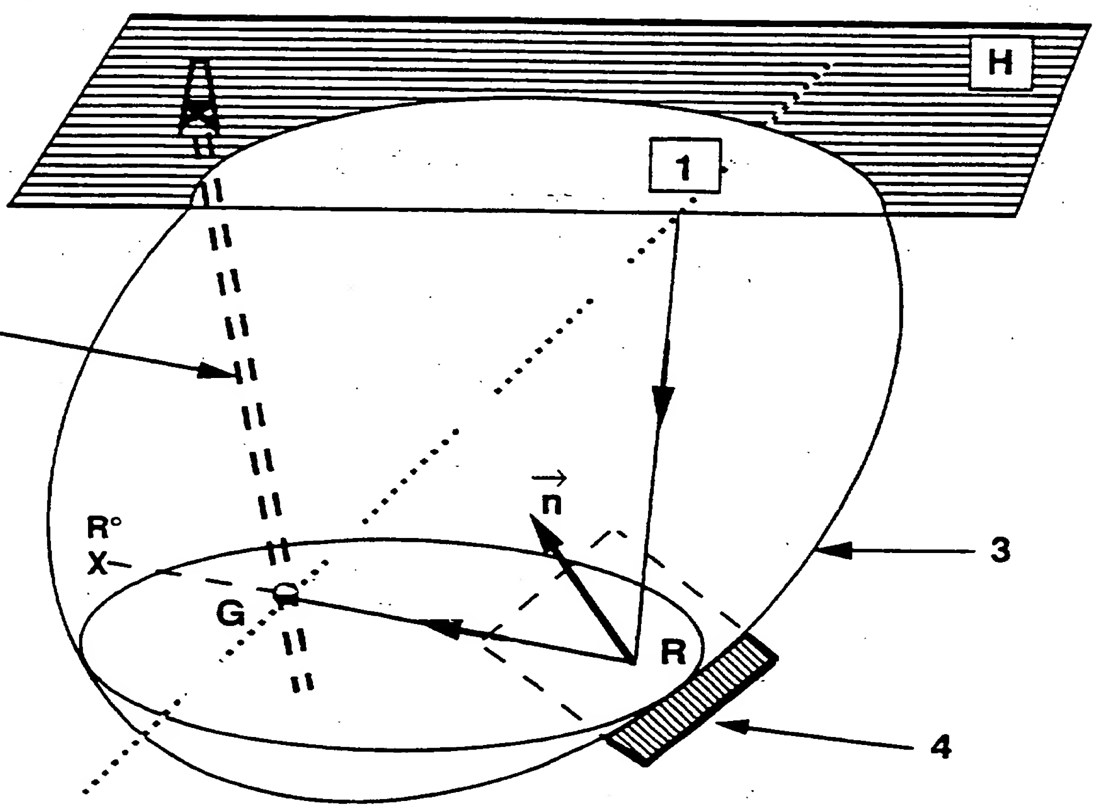


Fig. 2

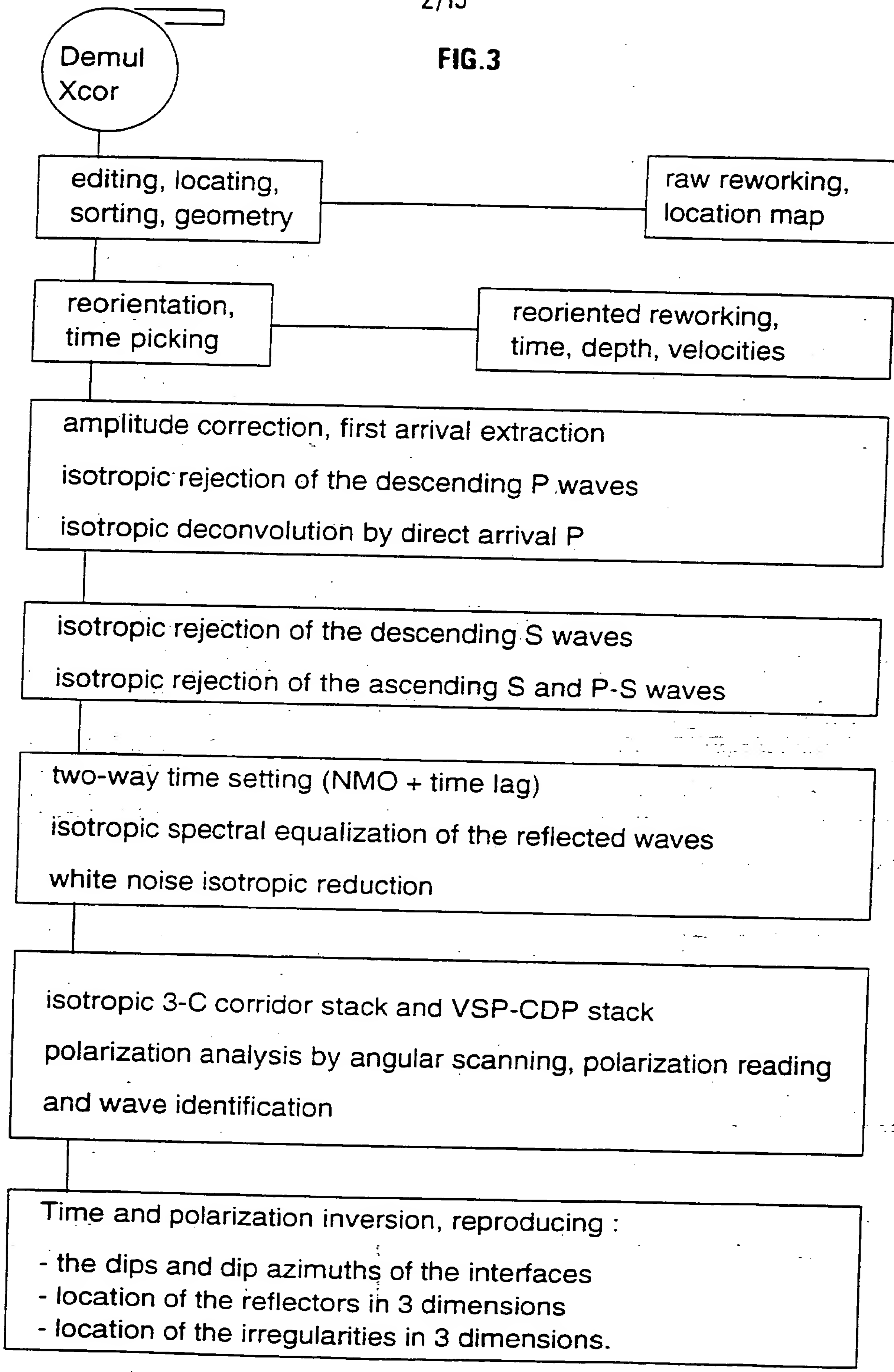

Demul
Xcor
editing, locating, sorting, geometry
raw reworking, location map
reorientation, time picking
reoriented reworking, time, depth, velocities
amplitude correction, first arrival extraction
isotropic rejection of the descending P waves
isotropic deconvolution by direct arrival P
isotropic rejection of the descending S waves
isotropic rejection of the ascending S and P-S waves
two-way time setting (NMO + time lag)
isotropic spectral equalization of the reflected waves
white noise isotropic reduction
isotropic 3-C corridor stack and VSP-CDP stack
polarization analysis by angular scanning, polarization reading and wave identification
Time and polarization inversion, reproducing :
- the dips and dip azimuths of the interfaces
- location of the reflectors in 3 dimensions
- location of the irregularities in 3 dimensions.

FIG.3

FIG.4

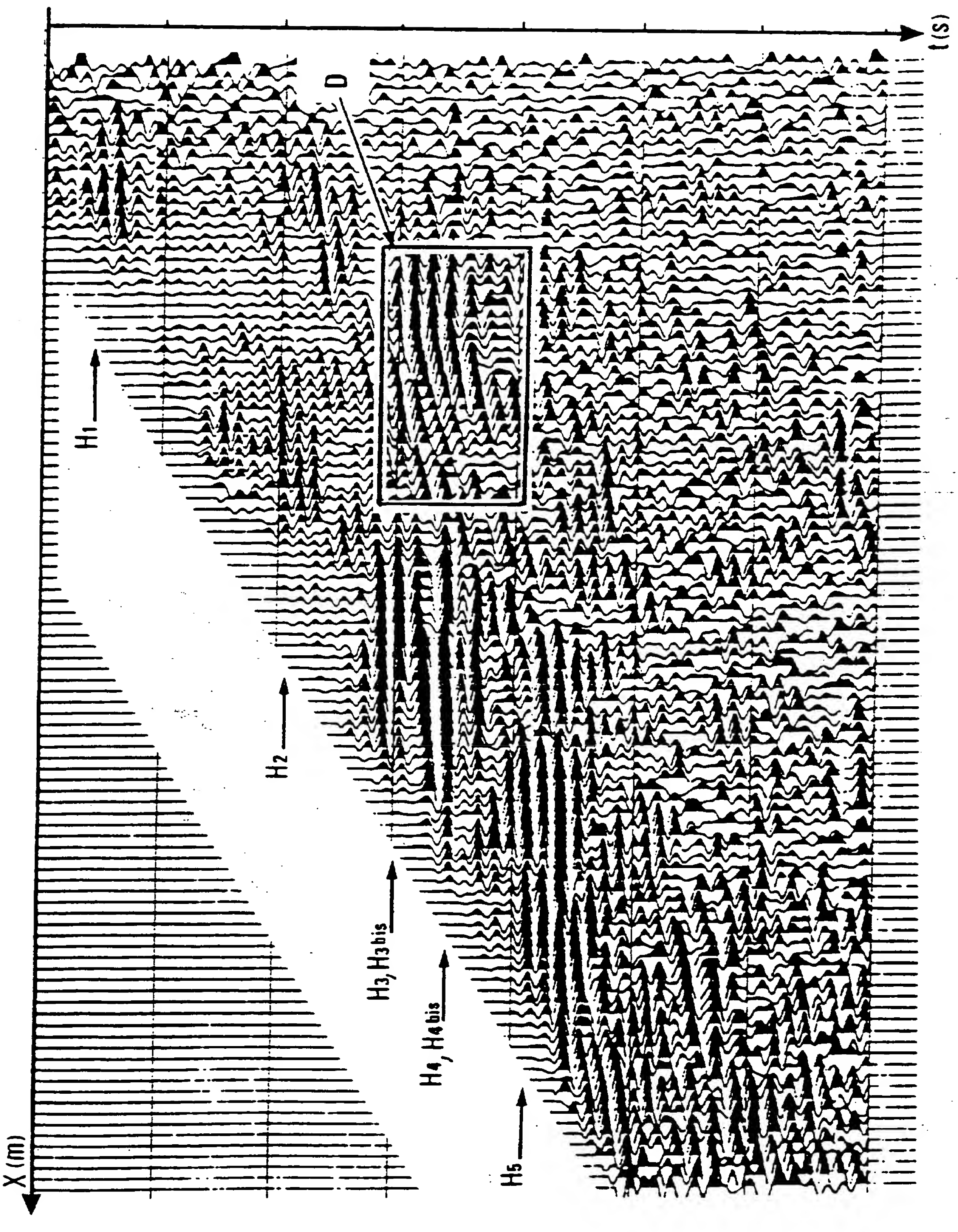
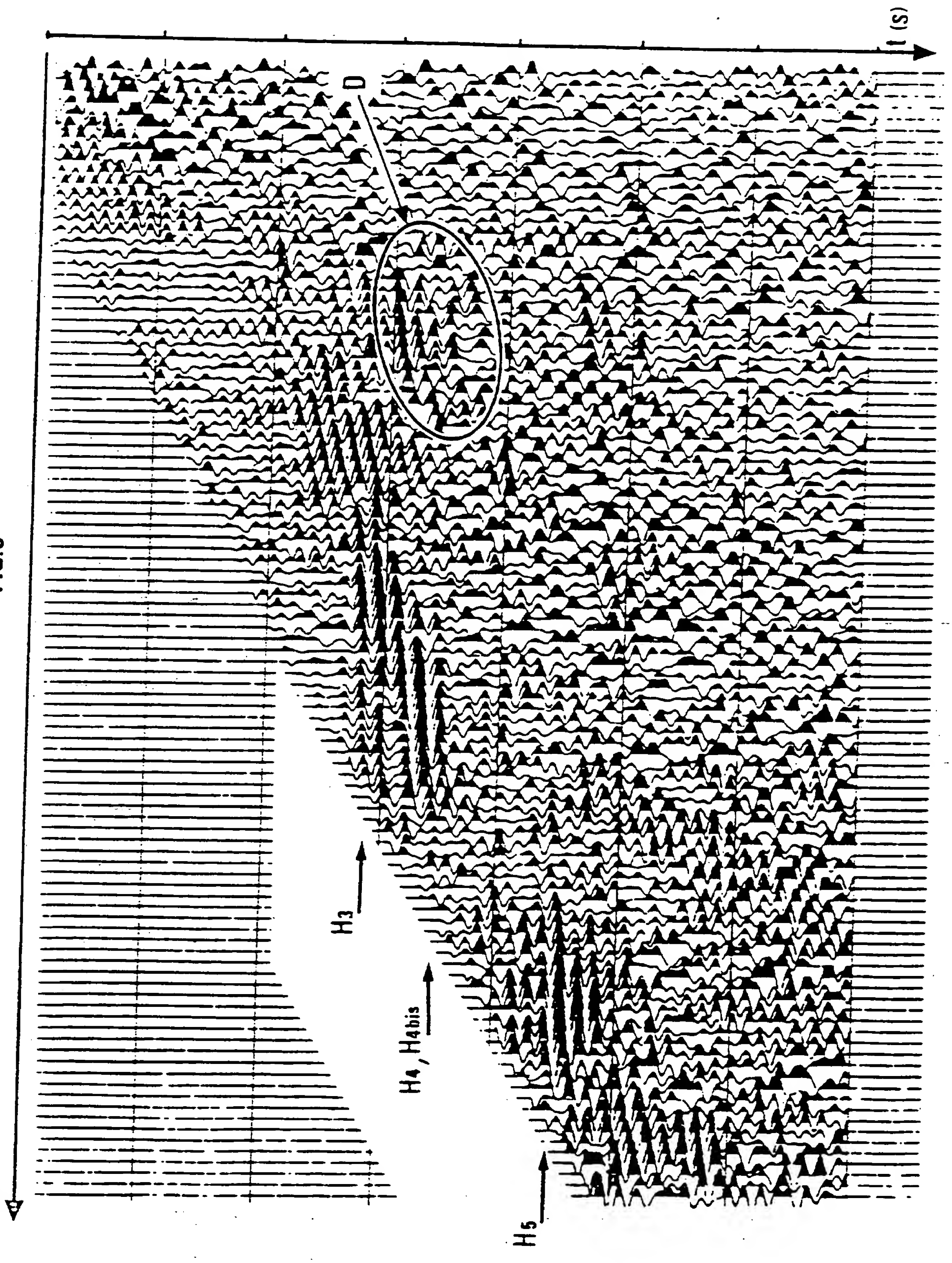


FIG.5



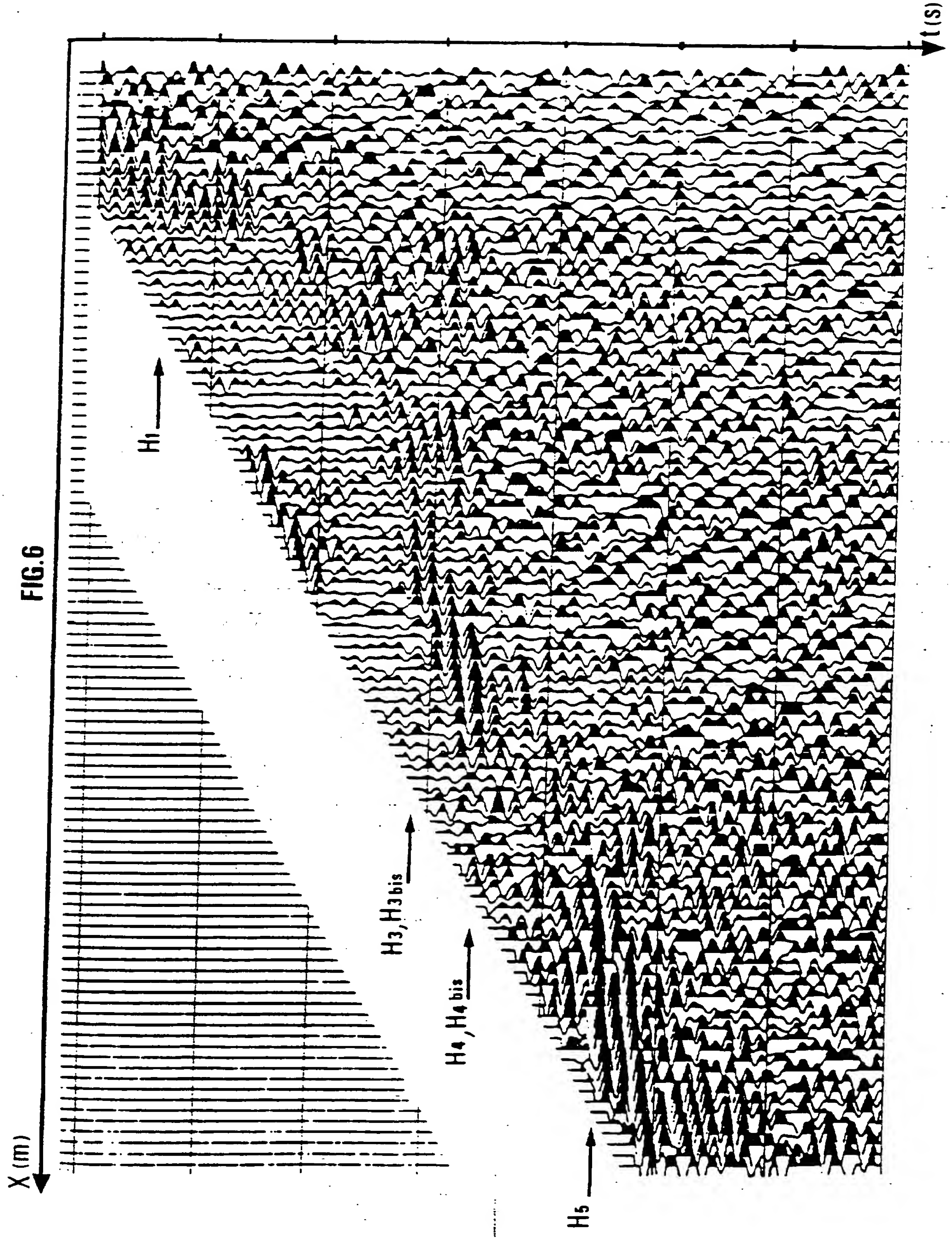
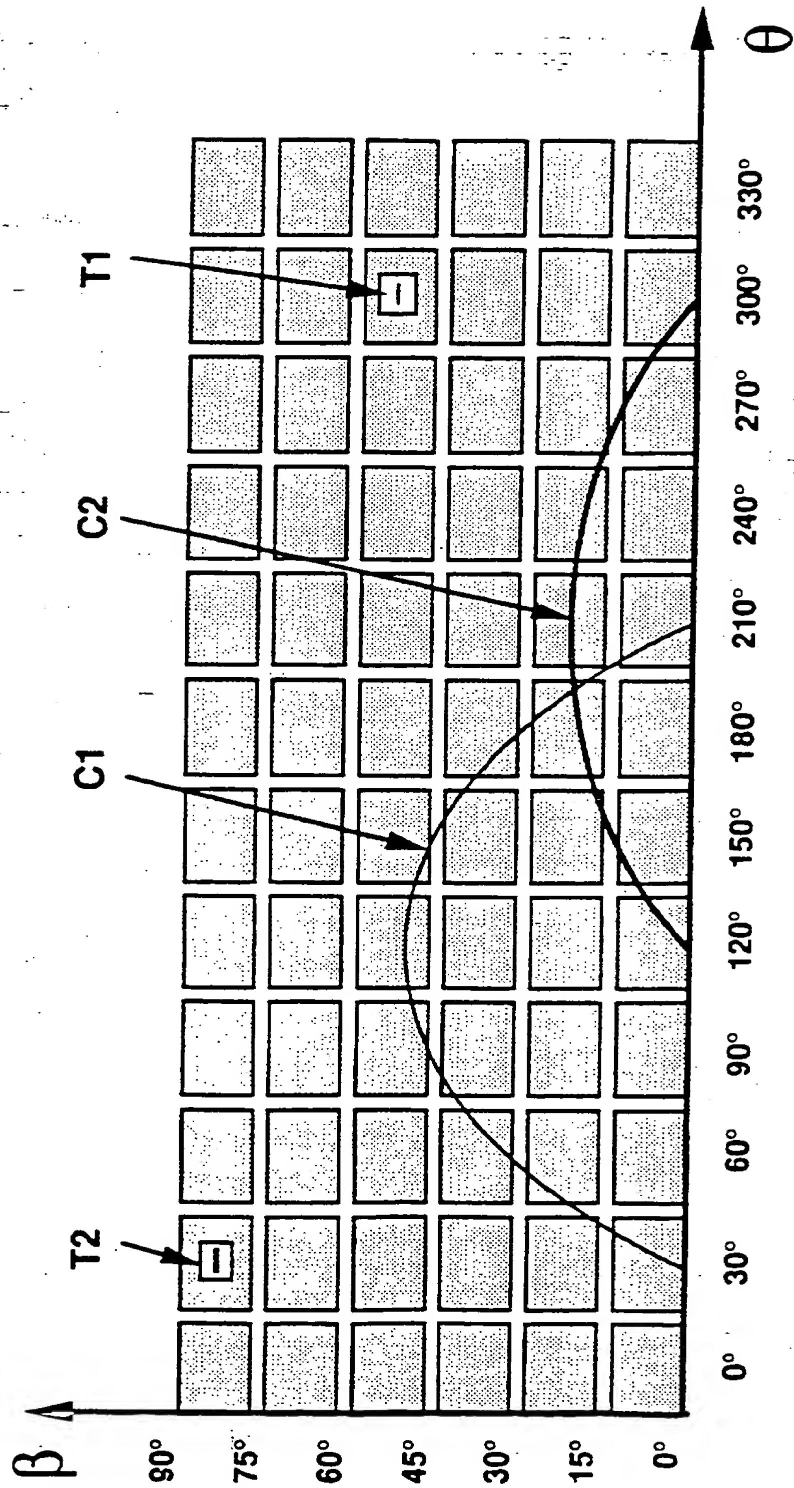


FIG.6

Fig. 7



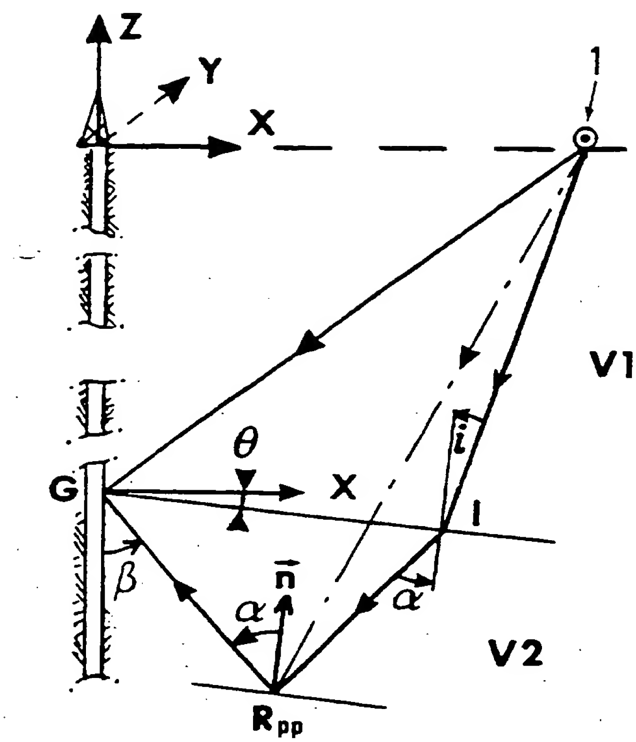


Fig. 8a

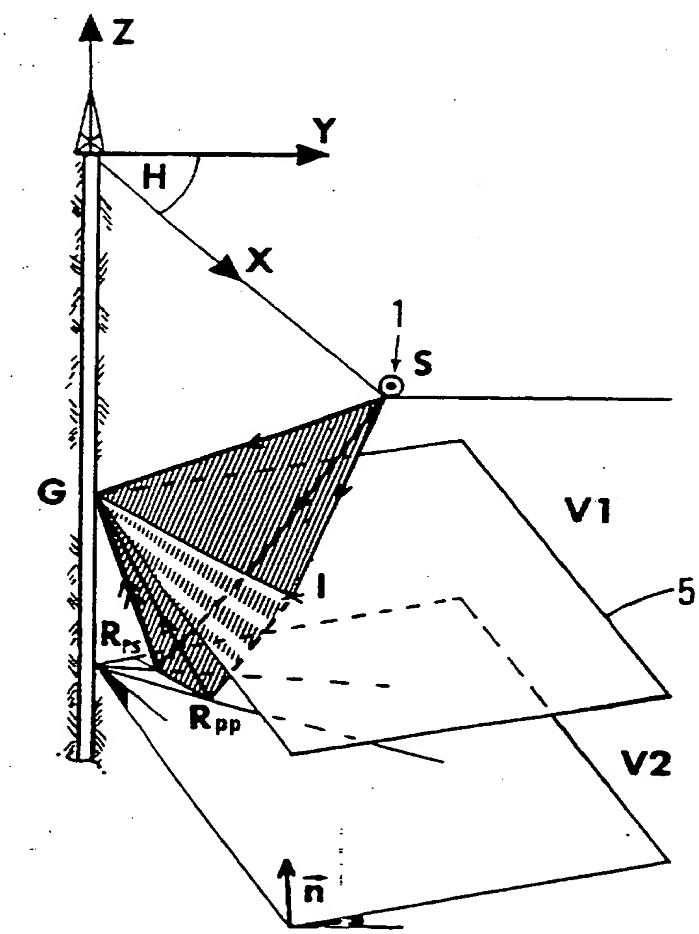
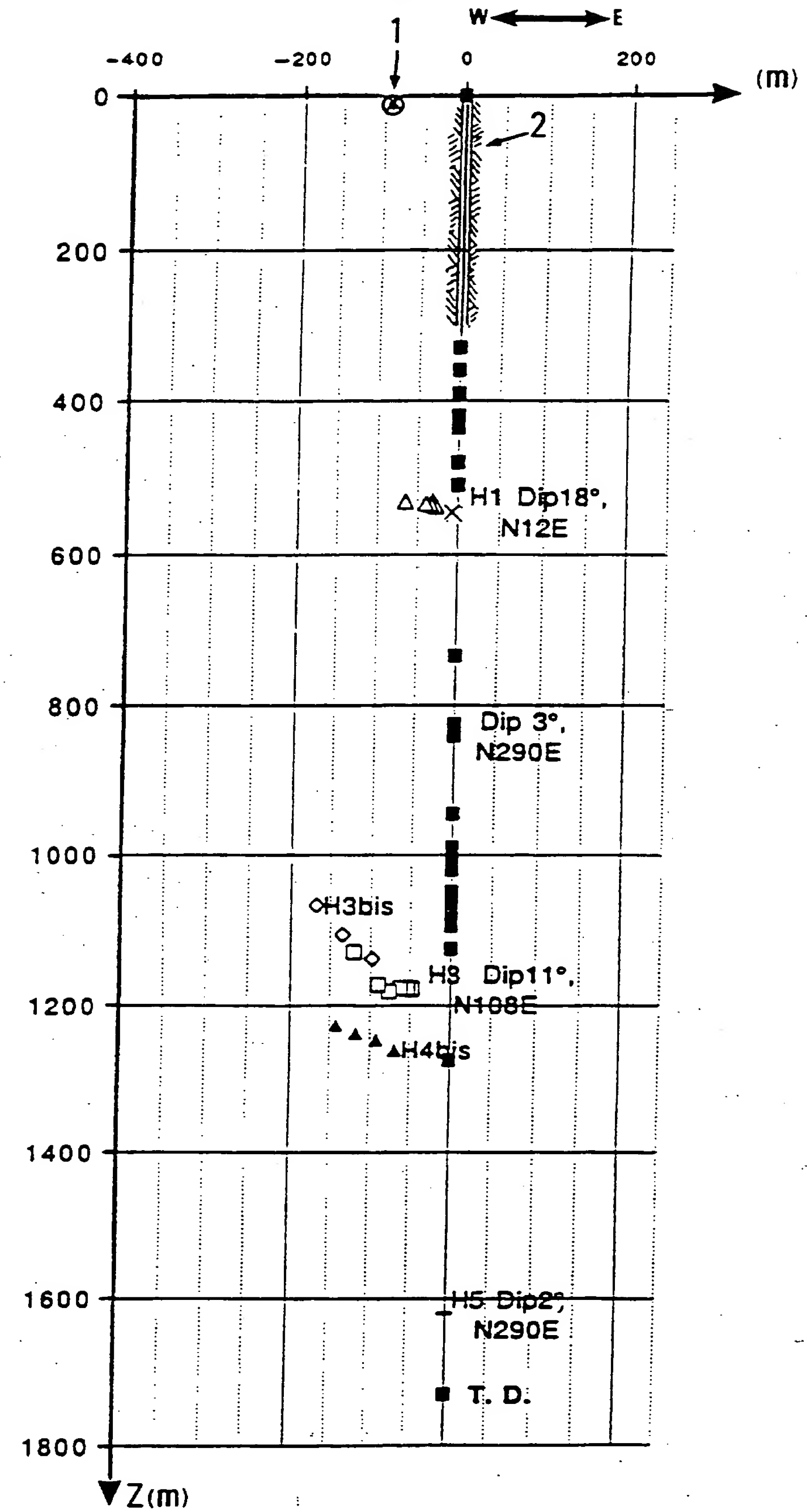


Fig. 8b

FIG. 9


W
E
1
2
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-200
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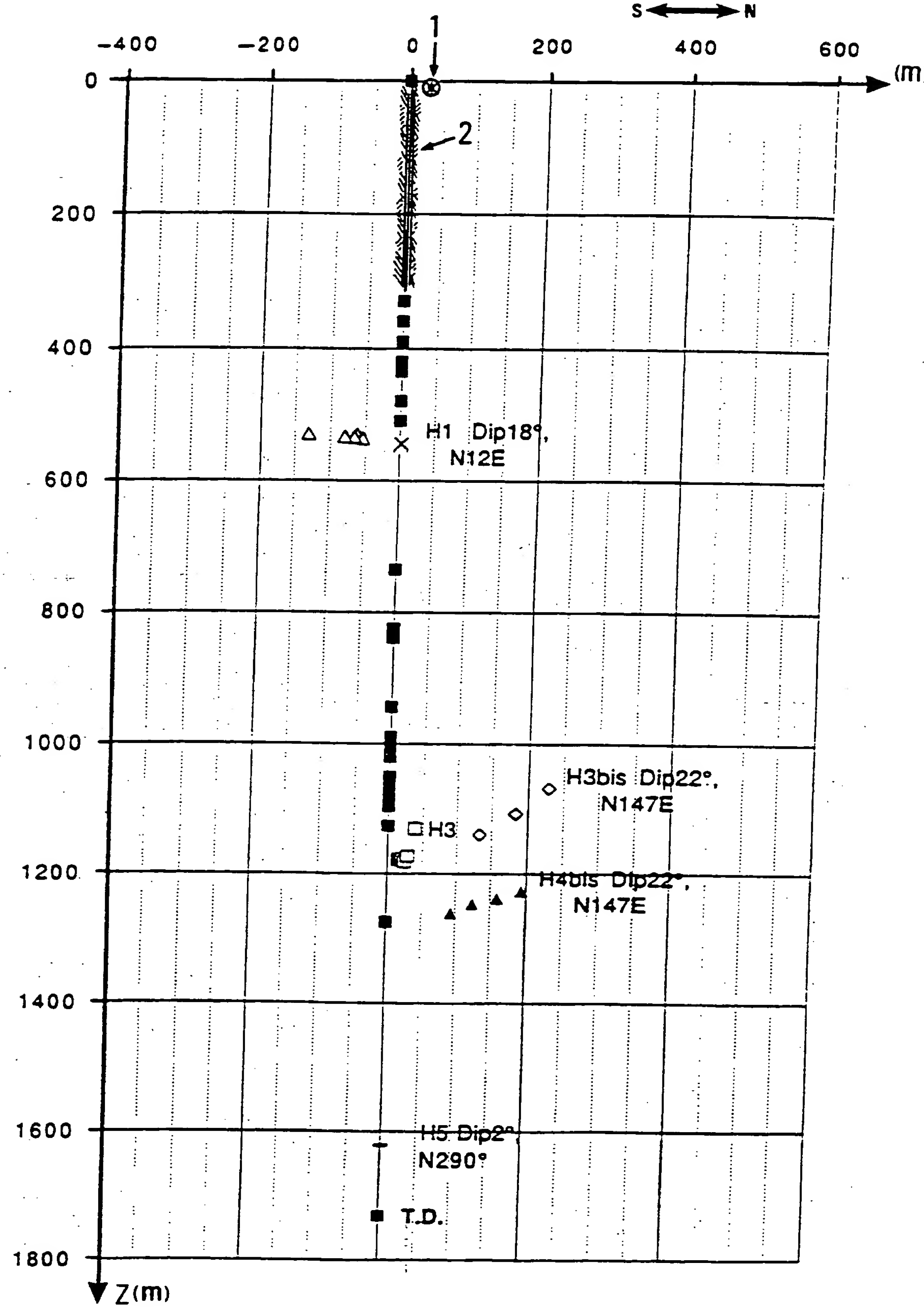
(m)
0
200
400
600
800
1000
1200
1400
1600
1800
Z(m)
H1 Dip18°,
N12E
Dip 3°,
N290E
H3bis
H3 Dip11°,
N108E
H4bis
H5 Dip2°,
N290E
T. D.

FIG.10



S N
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(m)
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1200
1400
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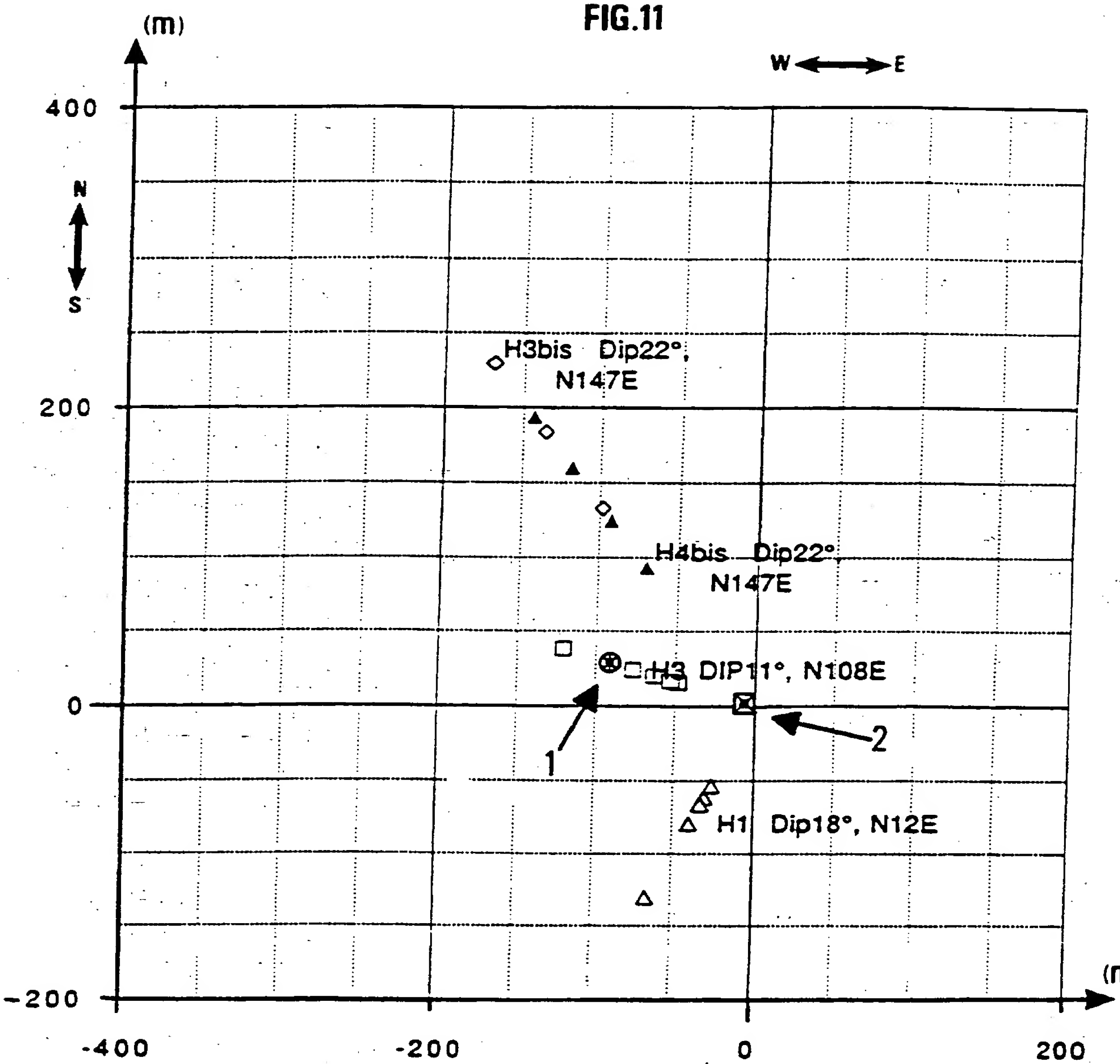
Z(m)
H1 Dip18°,
N12E
H3bis Dip22°,
N147E
H3
H4bis Dip22°,
N147E
H5 Dip2°,
N290°
T.D.

FIG.11


(m)
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H3bis Dip22°,
N147E
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H4bis Dip22°,
N147E
H3 DIP11°, N108E
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H1 Dip18°, N12E
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(m)
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-200
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FIG.12

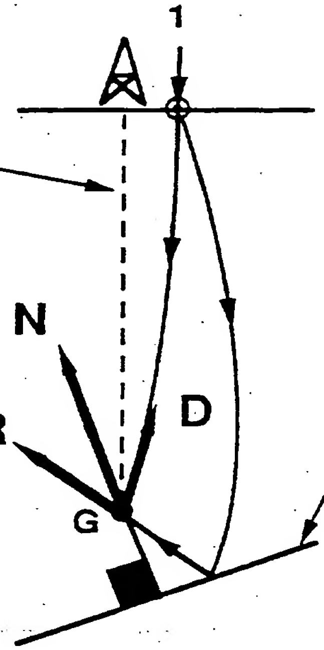


FIG.13B

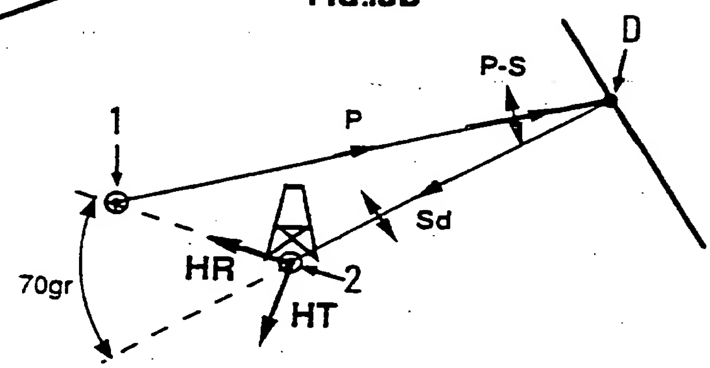


FIG.13A

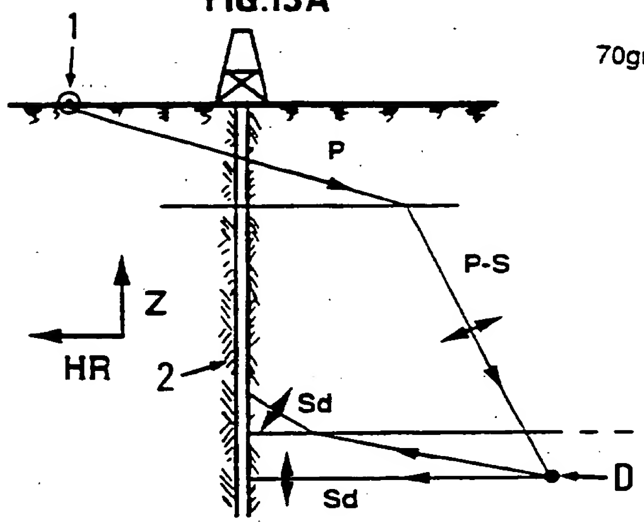
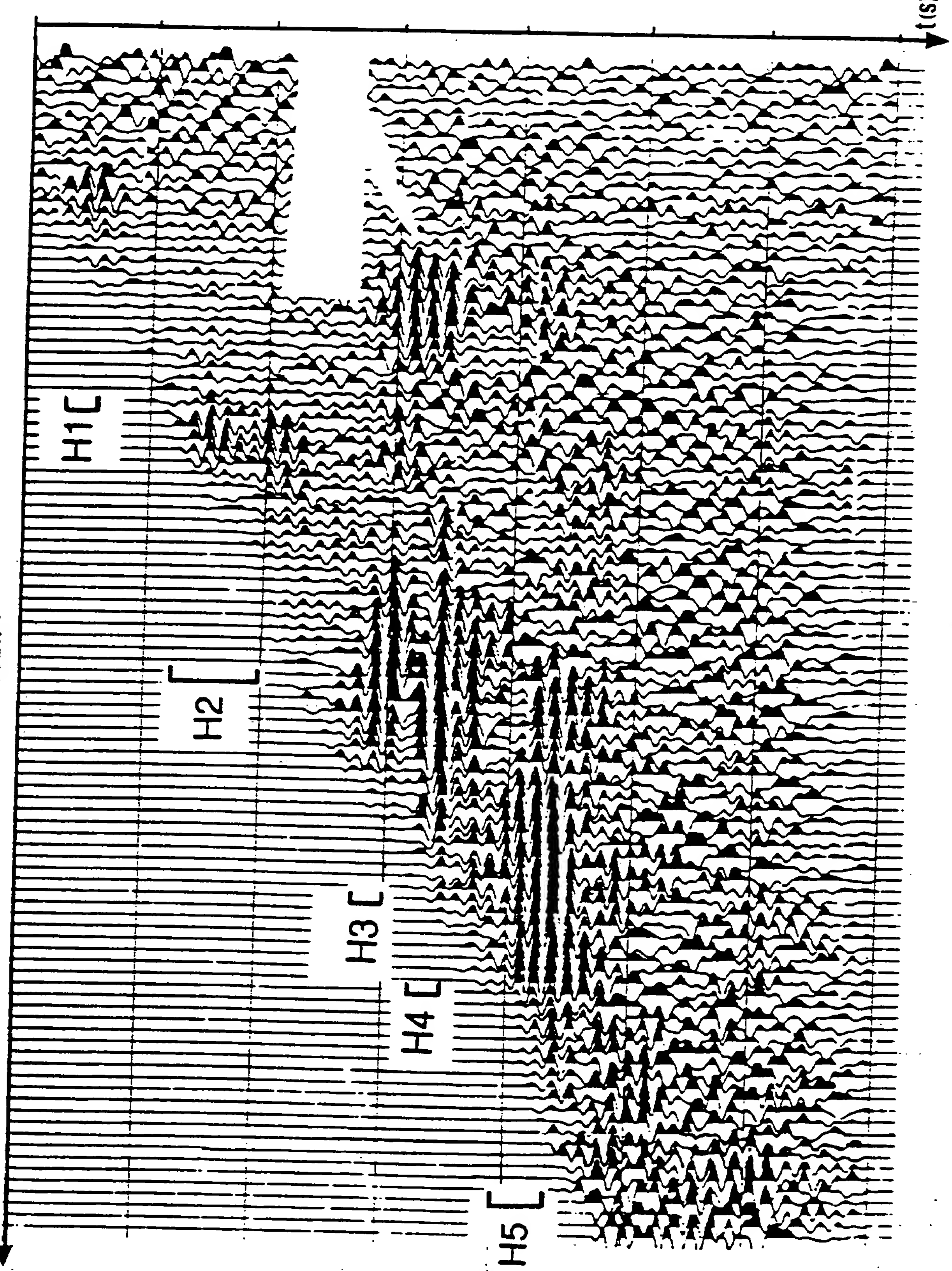


FIG.14



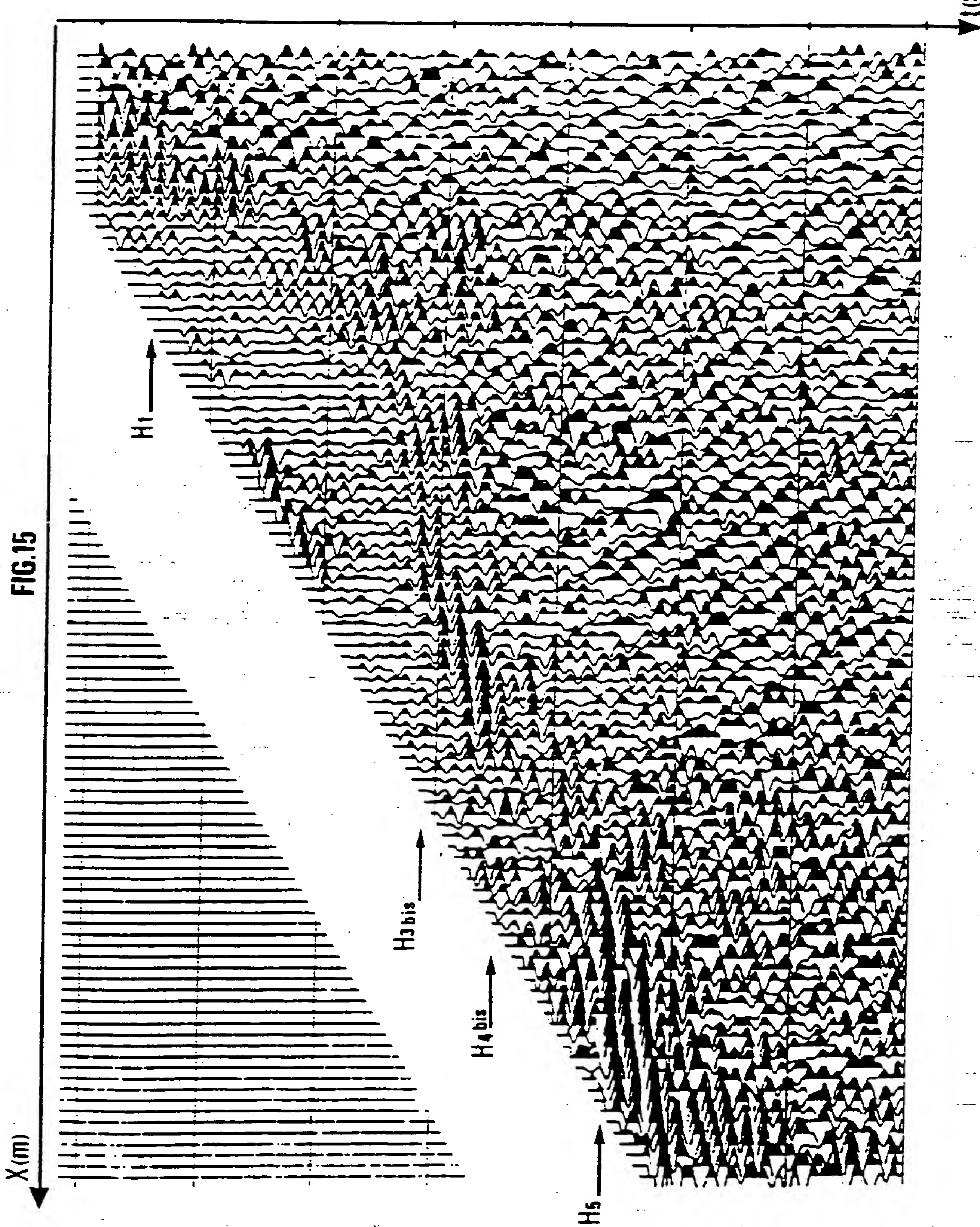


FIG.15

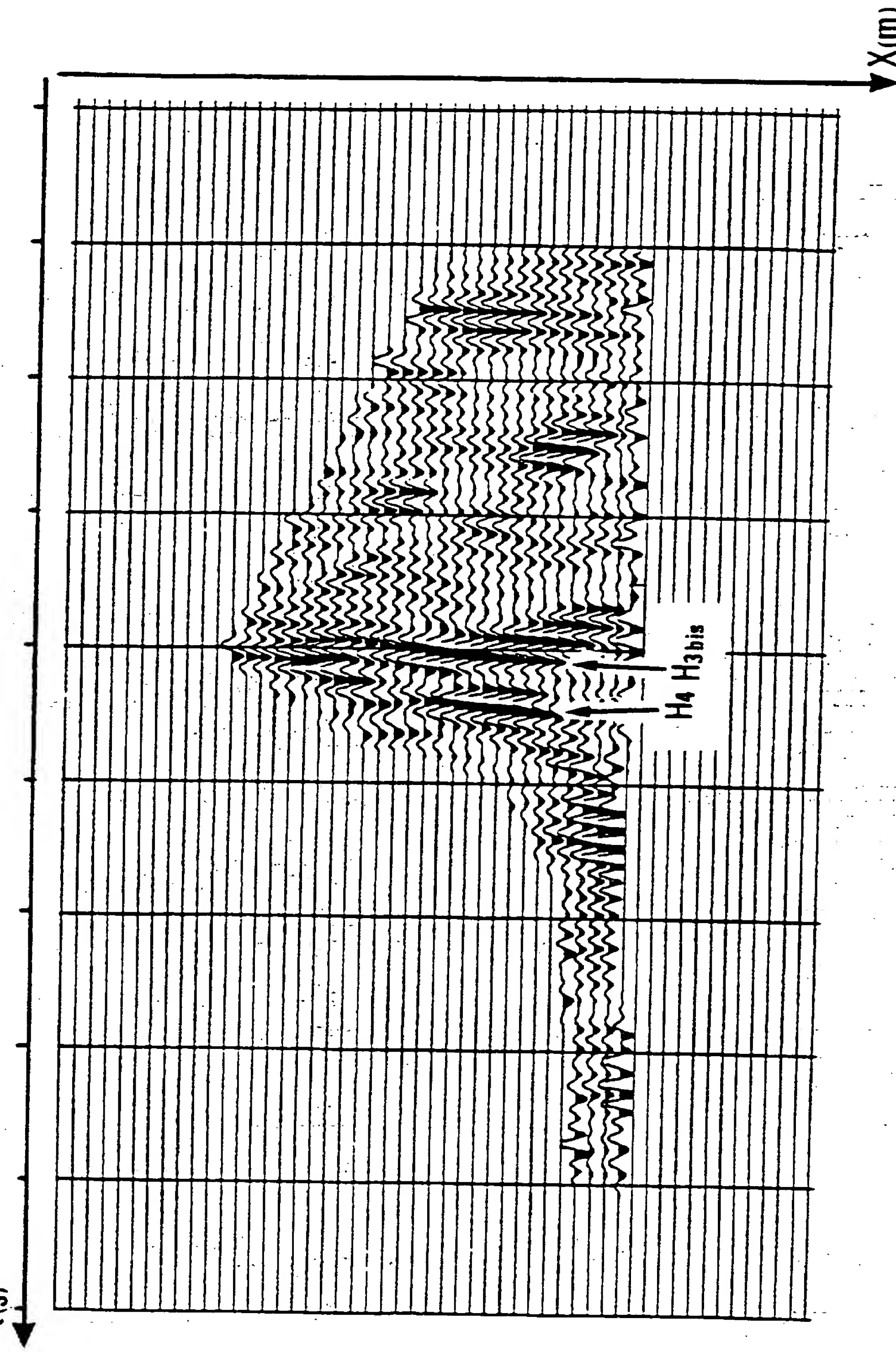


FIG.16

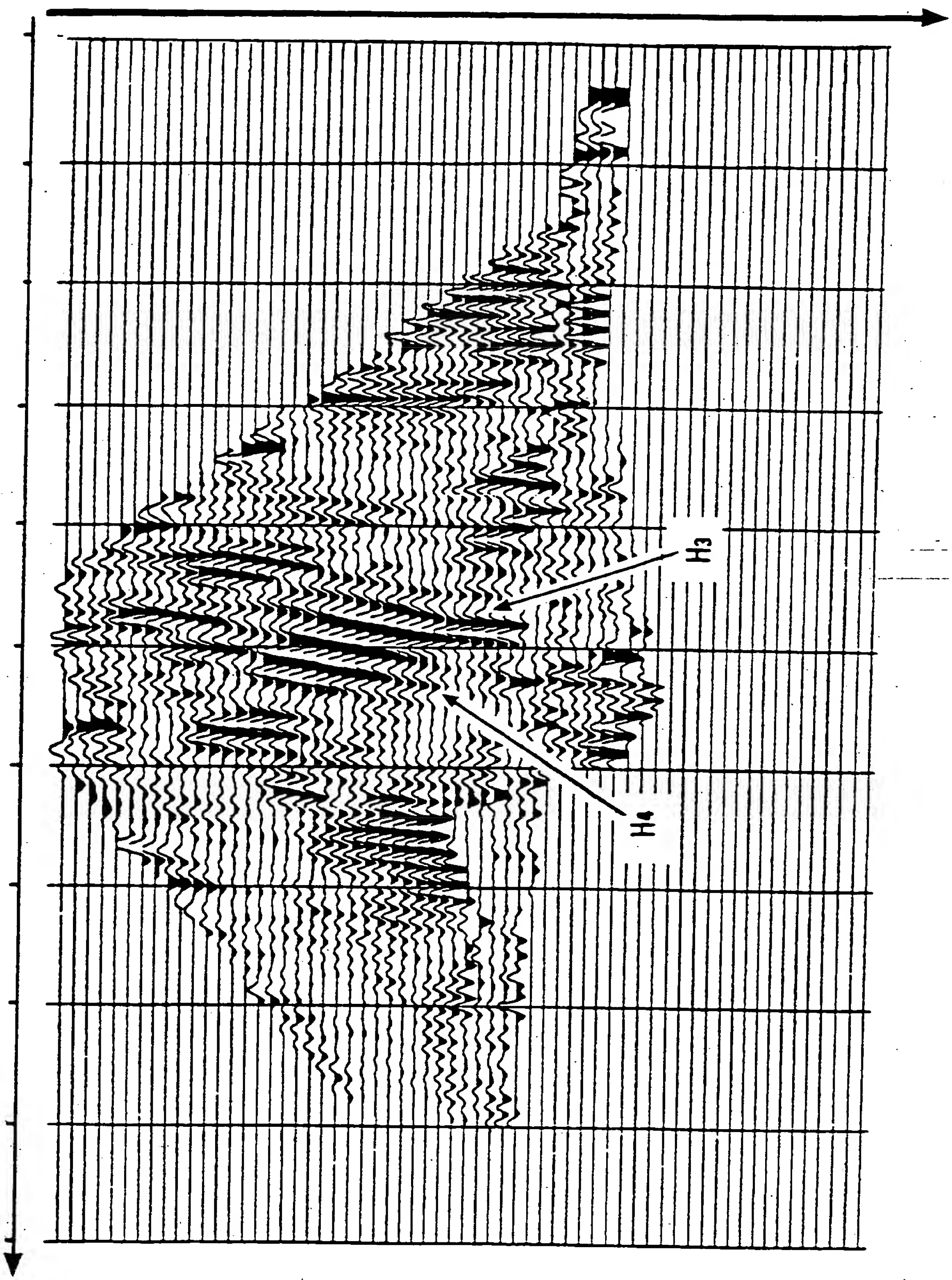


FIG.17

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METHOD OF PROCESSING ORIENTED, MULTI-COMPONENT, SEISMIC WELL DATA

The present invention relates to a method of processing oriented, multi-component seismic data obtained in a receiving well and more specifically seismic data obtained during vertical seismic profiling (VSP) operations in which the seismic waves are received by one or more multi-axis sensors coupled with the formations surrounding a well and a seismic source placed at the surface, either in the same well as the sensors or in another well.

The method of the invention finds applications in situations which involve seismic studies of the VSP type conducted in accordance with several known techniques: using a single or multiple offset source, by displacing the source along a profile passing through the uphole of the well, referred to as "walkway", or VSP in a deflected bore, for example, displacing the source directly above receivers in the well, a technique referred to as "walk-above", 3D VSP, on signals recorded by means of sensors in a well sonde or recorded during drilling (VSP-WD) or recorded using permanent seismic sensors as described in particular in patents 2 593 292 (US 4.775.089) and 2 656 034 (US 5.181.565) filed by the applicant.

Background to the invention:

When handling seismic data acquired by a VSP type

method using multi-axis sensors, for example, it is common practice to process one of the components, generally the vertical component. Examples of mono-component processing of seismic data are described in particular by:

- Hardage, B.: "Vertical Seismic Prospecting"; in Geophysical Press vol. 14, 1983;

or

- Mari, J.L. et al: "Seismic Well Surveying", 1991, Editions Technip, Paris.

Another known approach is to take account of the polarisation of direct waves, either as a means of re-orienting the components or for studying the area around salt diapirs.

However, this conventional approach of being restricted to one component leads to a certain degree of uncertainty when it comes to locating the geological events and this can not be eliminated. Inversion of times only leads to a multiplicity of solutions since the azimuthal directions of dip of the reflectors is unknown. Furthermore, when two seismic events occur at the same time with close apparent velocities and appear on several consecutive subsurface traces (6 to 12, for example), it is only too easy to see that it is virtually impossible to separate them by means of conventional mono-component processing.

The seismic prospecting method of the invention allows geological events to be located in space in the vicinity of the well. It consists in using multi-axis seismic sensors arranged in a well and coupled with the formations surrounding the well to receive components along three seismic wave axes sent back by discontinuities in the subsoil in response to seismic waves emitted in the ground by a seismic source (at the surface, either in the same well as the sensors or in a different well).

It is characterised in that it consists in assigning data to the acquired seismic data which will define the orientation of the multi-axis reception sensors in space, applying processing operators in parallel to the three components of the waves received which will make it possible to select from the waves received at each multi-axis sensor the polarised waves which can be used to characterise the geological structure in the vicinity of the well (in particular the reflected waves P or S as well as the arrivals of diffracted or refracted waves P or S), locate in space at each multi-axis sensor the respective directions from which these polarised waves have come and locate in space the seismic events which have generated said waves.

The method may involve forming a developed

cylindrical image, for example, made up of juxtaposed windows, each of which contains the seismic traces received in a given time slot coming from the azimuthal direction defined by the abscissa and the direction of inclination relative to the vertical defined by the ordinate so that the polarised waves can be distinguished by locating each seismic event in wave S by identifying the position of the window in which this event generates the strongest traces and each seismic event in wave S by identifying the position of the window in which this event generates the least strong traces.

The method may involve a combined step of inverting the times and polarisation of the reflected arrivals, in particular by ray tracing, using the azimuth and inclination of the direction from which seismic events have come in order to locate in space, in three dimensions, the position of points in the environment that have reflected, diffracted or refracted the waves, such as, for example:

- the reflection point that has reflected the ray as well as the azimuth of the plane tangent to the reflecting surface at the reflecting point;
- the point of diffraction acting as a secondary re-emission source; or
- the fault plane which generates a secondary

refraction.

The method may also incorporate an inversion restricted to determining the dip and azimuth of reflecting interfaces located in the immediate vicinity of the well (local domain stack, often referred to by specialists as "corridor stack"), in the thickness of the formation being surveyed by means of the VSP technique.

Other features and advantages of the method of the invention will become clear from the following description with reference to the accompanying drawings, in which:

- Figs. 1, 2 illustrate the principle used to locate in space the position of seismic events reflecting waves P by means of multi-axis seismic receivers;
- Fig. 3 is a flow chart summarising all the operations to be performed in order to implement the method of the invention;
- Figs. 4, 5, 6 respectively show an example of a field of reflected three-component waves P obtained by isotropic extraction from vertical two-way time VSP records using a source in the immediate vicinity of the well in which a seismic event D appears;
- Fig. 7 gives a schematic example of a developed cylindrical projection which can be used to

identify waves by their polarisation and locate the azimuth and inclination relative to the vertical of the direction from which seismic events of linear polarisation have come, where seismic events exhibit a maximum;

- Figs. 8a, 8b illustrate, on a simple model, the principle of inversion by ray tracing in space and in an incident plane of the reflected ray respectively;
- Figs. 9, 10, 11 show the projection in two vertical planes and one horizontal plane respectively of the locations of seismic events located on the records of Figs. 4 to 6, which can be located by implementing the method of the invention;
- Fig. 12 illustrates the simplified case of an inversion procedure which can be applied in the immediate vicinity of a well;
- Figs. 13a, 13b show the vertical and horizontal projections of the direction in which an incident wave P-S, converted into a wave S by a scatterer, is propagated, corresponding to the event D of Figs. 4 to 6 after inversion of the arrival times and polarisation of the diffracted arrival;
- Figs. 14, 15 represent the reflected wave fields separated after analysis by cylindrical

projection, which are used to produce common-depth-point images, a term that is understood in the description below to be what specialists refer to specifically as "VSPCDP stack";

- Fig. 16 shows the common-depth-point image of horizons H3, H4 with a dip of 12° in the azimuth N 108°E at approximately 0.5 sec. in two-way time in Fig. 15; and
- Fig. 17 shows the common-depth-point image of horizons H3a, H4a with a dip of 22° in the azimuth N 147°E situated at about 0.5 sec. in two-way time in Fig. 15.

Description of the method:

The method of the invention is implemented using multi-axis sensors such as tri-phones coupled with the formations surrounding a well and a seismic source positioned at the surface, in the same well as the sensors or possibly in another well close by. It applies the simple principle defined below. In a simplified model with constant propagation velocity (Fig. 2), the locus of the points that have reflected waves emitted from a point of emission 1 and captured after being reflected at another point G of a well 2, corresponding to a same propagation velocity vt is, as is known, an ellipse of revolution 3 having points 1 and G as the foci. It is also known that the

propagation direction of waves P is co-linear with the direction in which particles move in the propagation environment. By combining in amplitude and phase the three components (two H components and one Z component) received by a three-axis geophone located at the point G, it will be possible to determine the direction in space from which the pressure waves have come and hence the local orientation of a reflector which is a plane 4 tangent to the ellipsoid 3 and of the normal n thereof. This can be used to derive the angle of dip i/2 of the reflector that reflected these waves, which, in the very simple case where the seismic source and the reflector are placed in the immediate vicinity of a vertical well, is equal to half the angle i of inclination of the rays relative to the well axis, as illustrated in Fig. 1.

The principle outlined above will be applied below to complex environments more representative of the structure of the subsoil in order to restrict the possible structural patterns in the vicinity of a well to a single solution. Beforehand, it will be necessary to single out from the waves received those which correspond to the reflected pressure waves.

The method of the invention consists in running a series of processing steps as described below on raw seismic signals received by one or more three-axis

seismic sensors or tri-phones coupled with the formations surrounding a well, either sensors placed in tools, sondes lowered into a well on the end of a cable or stationary sensors installed permanently as described in the patents of the applicant mentioned earlier. The set of processing operations applied to the captured signals is illustrated in the flow chart of Fig. 3.

1 - **Re-orientation** : The raw seismic data received by the sensors must be combined with data which will allow the three components to be re-oriented in space. Several situations may occur:

In a substantially vertical well, different means can be used to detect the orientation data to be combined with the captured seismic data. These may be magnetic orientation means which locate the direction of the earth's magnetic field if operating in an open hole and/or inclinometers or, less often in view of the high cost, a gyroscope. The orientation measurements of the components can then be taken accurately in an open or a cased well.

In a deflected well, whose trajectory is known and generally measured separately by means of a tool equipped with a gyroscope, the three-axis sensors are mounted on a cardan coupling so that the orientation of the components can be ascertained accurately.

In the case of a vertical cased well or a deflected well whose trajectory is ascertained by taking recordings using three-axis sensors fixed relative to the body of a tool, it will be possible, under certain favourable conditions, to use the polarisation properties of the direct seismic waves P to re-orient the components located in the plane perpendicular to the well axis. To this end, the direct arrivals must not be in a plane parallel with the well axis and this re-orientation will only be valid for the logging in progress. This re-orientation stage is well known to those skilled in the art and is described, for example, by:

- Becquey M. et al in Geophysics, 1990, vol. 55 _ 10, pp. 1386-1388;

and can be implemented using re-orientation software such as Géovecteur® by Compagnie Générale de Géophysique. The accuracy obtained is approximately ±5°, which is enough to proceed successfully with the processing outlined below.

2 - Isotropic extraction of the useful seismic waves in three components

If the aim is to measure polarisation parameters of the movement of particles in space on the basis of signals received by the three-axis sensors, the phase and amplitude differences between the components will

have to be retained during all the previous processing operations.

In particular, the seismic signals obtained in VSP-3C will have to be put through the conventional processing operations listed below, which will have to be applied in an identical fashion to the three components of the signals and preferably in the order listed in the flow chart of Fig. 3.

* Multi-trace filtering to separate events having different apparent velocities, either in an absolute reference set of geographic data or in a local geographic reference set relative to a sub-set of consecutive traces of a wave separation algorithm, designating under the term trace a three-component signal recorded at a given point in space,

* dynamic equalisation, deconvolutions regardless of their type,

* static corrections and dynamic corrections (moveout),

* mono-trace or multi-trace addition/subtraction,

* random noise reduction, etc..

The term processing isotropy is used here to mean that the same mono-trace or multi-trace mathematical operator is applied to the three components of each trace at the same instant and the operator may vary depending on the seismic arrival time. Any signal

processing algorithm which exhibits this feature can be termed isotropic and can advantageously be used to process well data with three components, in particular as a means of eliminating unwanted arrivals in order to isolate the seismic arrivals sought. An example of the result of this isotropic extraction is given in Figs. 4 to 6, mainly showing the three-component reflected wave field in vertical two-way time.

3 - **Analysing the polarisations of the arrivals sought after isotropic extraction :**

Generally speaking, the sought arrivals are mainly the pressure wave reflections (wave P) and the diffractions in wave P of linear polarisation parallel with the direction of propagation or the diffractions in waves S of linear or elliptical polarisation in the plane substantially orthogonal to the direction of propagation.

If only one wave type is present at a given depth and time of arrival and within an acceptable range of apparent velocities on the field of reflected waves P with three components, the polarisation thereof can be measured directly (linearity or flatness, orientation of the polarisation) on a single three component trace and at a given time. The apparent velocities and the polarisation type can be used to identify the wave type (P or S) to be processed and to deduce therefrom the

direction of propagation.

On the other hand, if several wave arrivals of the same type or different types reach the same sensors almost at the same time and have very close apparent velocities and hence are from different sources, it is more difficult to separate them from one another. An analysis and direct reading procedure by angular scanning, described below, is therefore used to identify and separate the three-component wave field into discrete unitary events.

As illustrated in Fig. 7, a two-dimensional multi-window table is set up to represent a cylindrical projection in which the azimuth θ between 0° and 360° is on the abscissa with, on the ordinate, the angle of incidence β of the arrivals between 0° and 360° relative to the vertical. Each window represents the seismic traces received in a given time slot coming from the direction indicated by the abscissa and ordinate which corresponds to its position in the table. In a cylindrical projection of a semi-sphere, the intersection circle with a plane passing through the centre appears as a substantially sinusoidal curve centred on the equator. It is in this form that lines C1 and C2 appear in Fig. 7, respectively joining the points of the different windows where two linearly polarised seismic events, respectively E1 and E2, can

no longer be located. The azimuths of the windows, T1 and T2 respectively, where these same events exhibit an observable maximum are at 90° respectively from the foot of the two curves C1, C2. A graphical presentation such as this is convenient as a means of distinguishing between the interfering arrivals more readily and of directly identifying the wave types observed and their number.

It may be completed by automatic processing programmes which will allow the various seismic events detected to be isolated.

4 - Time inversion and polarisation of the reflected arrivals observed

In the fourth place, the method involves an inversion procedure which uses a conventional ray tracing programme, for example, in a velocity model with or without layer anisotropy, which must comply with the velocities measured at the well W and the dips observed on the reflectors positioned between the surface source and the three-axis sensors G in the well. The reflected part of the ray can be traced by emergence from the sensors in a cone of uncertainty around the measured spatial direction of polarisation of the reflected ray. An example of propagation in a simplified formation model with two propagation velocities V1, V2, is illustrated in Fig. 8a (spatial

representation) and Fig. 8b (projection in the plane of propagation of the reflected ray). By ray tracing in such a model, the position of the reflection point Rpp of co-ordinates (xr, yr, zr) can be determined where the pressure waves received at point G come from using the angle of inclination β and the angle of azimuth θ, as well as the normal vector n at Rpp at the reflector 5. The different reflection points of the pressure waves received, located by this inversion, can be represented in space. For the sake of ease, they can be represented by their projections in different planes. Figs. 9, 10 correspond to projections of the reflection points in two vertical planes oriented respectively West-East (W,E) and North-South (N,S) whilst Fig. 11 corresponds to their projection in a horizontal plane.

It is clear that, for example, the events H3 and H3a as well as H4 and H4a which appear to be interfered in Figs. 4, 5, 6 are distinctively represented by the proposed method as two illuminations of a same horizon on Figs. 9, 10, 11, which would be impossible if mono-component processing were applied as is the case with the known methods.

The method therefore provides a single solution from the VSP data alone, regardless of any other data, which provides very useful data for the geologists who are the end users of the results.

The inversion procedure described above can be simplified considerably in the zone surrounding the well where trace stacking is performed along a corridor centred on the first arrivals, a technique referred to as "Corridor Stack" by specialists. It may be assumed in this case that the normal N to a reflector 6 (Fig. 12) is the bisector between the propagation direction of the direct ray D and the propagation direction R of the reflected ray for the reflection domain in the immediate vicinity of the well (Descartes' law).

Inversion of high-energy major diffractions and refracted waves:

If high-energy anomalies of the diffraction type or secondary refraction are observed, such as the hyperbolic arrival of D (Fig. 4, 5), the type of wave received by the sensors firstly has to be identified (wave P or wave S) in order to assign a propagation velocity to these singularities in the vicinity of the sensor (velocity P or velocity S, these velocities being measured by means of the corresponding direct arrivals). An anomaly is generally linked to the presence of a geological irregularity in the vicinity of the well such as a high-velocity fault or heterogeneity. A well-informed geophysicist knows how to identify types of anomaly and the seismic paths associated therewith.

Once this identification process has been completed, an inversion combining the times of arrival of these anomalies and their polarisation can be used to ascertain the depth or depth extension of the irregularity that has generated them as well as the distance between the latter and the well in the azimuthal direction of the geological irregularity.

The result of this operation is, for example, that the anomaly D observed on Figs, 4, 5, is structurally reproduced in the diagrams of Figs. 13a, 13b in vertical projection Fig. 13a) and in horizontal projection (Fig. 13b). On seeing these results, a geophysicist will be able to explain to the geologist that the ascending branch of the diffracted wave Sd, for example, has reverse polarities on components Z and HR (horizontal) and therefore that the diffracting event D is located in the semi-plane beyond the wall 2 relative to the source 1.

5 - **Imagery** :

The method may then incorporate a 3D point by point representation of the migrated reflected arrivals leading to a single solution of a geological structural pattern. This pattern, with the associated velocities and dips, can be used as a model to produce a 2D multi-azimuth VSP common-depth-point seismic image (of the VSPCDP stack type) or even a real 3D VSP common-depth-

point image (VSPCDP-3D) by using known processing and imaging software. As seen above, Figs. 14, 15 represent the reflected wave fields separated after analysis by cylindrical projection which are used to produce common-depth-point images. Figs. 16 and 17 correspond to the time images of the two families of reflectors H3, H4 and H3a, H4a detected and represented on Figs. 9, 10, 11 above with respective dips of 11° (Dip 11°) and 22° (Dip 22°) in the respective azimuths N108°E and N147°E relative to the well which are visible at approximately 0.5s in two-way time.

It is also possible to produce a 3D representation of scatterers corresponding generally to a 3D alignment of singular scatterers, for example a fault crest or an erosion cliff boundary and detected fault planes as a series of scatterers.

Fault planes or high-velocity geological body borders (salt diapirs for example) can also be represented in 3D after inversion of the most obvious direct or secondary high-energy arrivals.

There are many techniques known to the person skilled in the art which can be used with all these representations to assist the end user, the geologist, in understanding and reading the images and their meaning in geological terms.

CLAIMS

1. A method of seismic prospecting which consists in using three-axis seismic sensors arranged in a well 2) and coupled with the formations surrounding the well to receive components along three axes of seismic waves returned by discontinuities in the subsoil in response to seismic waves transmitted through the ground from a seismic source (1) and assigning to the seismic data received data defining the orientation in space of the three-axis seismic receiving sensors, characterised in that it consists in applying processing operators in parallel to the three components of the waves received so that, from among the polarised waves received at each three-axis sensor, the waves which can be used to characterise the geological structure in the vicinity of the well can be selected, such as the reflected waves P or S as well as the diffracted or refracted arrivals P or S, the respective directions from which these polarised waves are coming can be located in space, at each three-axis sensor, and the seismic events which generated said waves can be located in space.

2. A method as claimed in claim 1, characterised in that it consists in building a developed cylindrical image made up of juxtaposed windows, each of them containing the seismic traces received in a given time

slot, coming from the azimuthal direction (θ) defined by the abscissa and from the inclined direction (β) defined by the ordinate, so that each seismic event in wave P can be distinguished by identifying the position of the window in which this event generates the strongest traces and each seismic event in wave S by identifying the position of the window in which this event generates the least strong traces.

3. A method as claimed in claim 1 or 2, characterised in that it incorporates a combined step of inverting the time and polarisation of the reflected arrivals previously measured so as to reconstruct in 3D the position in space of points in the surrounding area which reflected, diffracted or refracted the waves.

4. A method as claimed in the preceding claim, characterised in that it incorporates an inversion by ray tracing.

5. A method as claimed in one of the preceding claims, characterised in that it includes reconstructing dips in the immediate vicinity of the well.

6. A method as claimed in claim 3, characterised in that it includes representing seismic events by their projection in one or more planes.

7. A method as claimed in claim 5, characterised in that it includes representing in the form of dip

logs seismic events situated in the immediate vicinity of the well in the thickness of the formation.

8. A method as claimed in one of the preceding claims, characterised in that the seismic source (1) is positioned at the surface either in the same well as the multi-component sensors or in another neighbouring well.

9. A method of seismic prospecting substantially as hereinbefore described with reference to the accompanying drawings.

The Patent Office

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Application No:	GB 9802327.8	**Examiner:**	Grant Bedford
Claims searched:	1 to 9	**Date of search:**	27 May 1998

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): G1G (GMB)

Int Cl (Ed.6): G01V (1/28 1/30 1/40 1/42 1/44 1/48 1/50 1/52)

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	GB 2316485 A (WESTERN ATLAS)	-
A	GB 2292802 A (EXXON)	-
A	GB 2233454 A (COAL INDUSTRY)	-
A	GB 2209833 A (GYRODATA)	-

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